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A field-based assessment tool for phosphorus losses in runoff in Kansas

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Abstract: Nonpoint P sources from the agricultural landscape are a significant environmental problem for surface water bodies because of the promotion of eutrophication. Many states have developed P assessment tools to help differentiate land uses and their potential for P losses to surface water. Kansas has developed such a P index (PI), and the purposes of this paper are to report on the calibration of that index against data collected from four runoff studies and to explore the modification of the PI as a means to improve the predictive capability of the PI. The PI includes soil test P, rate and application method for P from fertilizers and manure, soil erosion, runoff class, distance from surface water bodies, and irrigation erosion as inputs. As originally proposed, the PI was well correlated with soluble P (r = 0.93) and bioavailable P (r = 0.94) losses but was less correlated with total P (r = 0.79). By modification of the PI, the r values improved to 0.97 for bioavailable P, 0.95 for soluble P, and 0.89 for total P. Of the 90 plots at four different sites, plots from Neosho and Franklin-1 and Franklin-2 sites were ranked as having very low and low vulnerability to P loss (82%) whereas plots in the Riley County site were ranked as high and very high vulnerability to P loss (18%) due to manure applications. Therefore, for only the Riley site, P management strategies need to be modified to reduce P losses. Moreover, additional P applications are not warranted for this site. Using soil test P as a single factor to predict P losses in runoff for our sites produced results similar to using the modified PI.

Key words: phosphorus—index—P losses—P runoff—soil test P—water quality

Phosphorus additions are integral and necessary for modern agriculture, but long-term and frequent applications of manure and biosolids result in very high soil test phosphorus (STP) concentrations because of imbalances between P inputs and outputs (Sharpley and Smith 1995; Sharpley et al. 1994; Beegle et al. 2000). The annual P surplus for agricultural land has reached 26 kg ha^{-1} (23.2 lb ac^{-1}) in the United States and 10 kg ha^{-1} (8.9 lb ac^{-1}) in the United Kingdom (Sharpley and Withers 1994). Phosphorus does not have a direct toxic effect on plant growth, but P can be a pollutant for the environment when it is transported by runoff and erosion to surface waters sensitive to eutrophication. Howarth et al. (2000) studied the effects of excess nutrients transported to coastal systems and stated that a considerable number of coastal systems in the United States have problems with excessive nutrients. They suggested increasing knowledge about eutrophication and developing strategies to reduce nutrient loading.

The loss of P in runoff is controlled to a large extent by transport (runoff and erosion) and source factors (soil P content and the amount, timing, method, and type of P applied). Controlling these factors can reduce P losses to a greater extent if they are implemented on targeted critical source areas in a watershed that is vulnerable to P losses in runoff (Sharpley 1995; Sharpley and Tunney 2000). Effective P management strategies have been developed to decrease P losses to surface water from point sources, but minimizing P losses from nonpoint sources has proven to be more difficult (Sharpley et al. 1994; Sharpley et al. 2003). In addition, the application of management plans on a large scale can be expensive, and different fields in a watershed contribute differently to P export from the watershed. In fact, it was reported that most of the P loss in a watershed comes from a small area of the landscape (Pionke et al. 1997; Gburek and Sharpley 1998). Identification of site vulnerability has been crucial for implementation of cost-effective management strategies (Sharpley 1995; Sharpley et al. 2000; Beegle et al. 2000; Kronvang et al. 2005). There are several tools for this purpose, such as computer-based water-quality models, field studies, and a phosphorus index (PI) (Sims et al. 2000). Another way to identify site vulnerability is to monitor STP (Sims et al. 2000). Models can be very accurate for predicting P losses, but they require detailed soil and management information (Sharpley et al. 2000). Field studies are time consuming, costly, and labor intensive (Sharpley 1995; Gillingham and Thurrold 2000). Therefore, there was a need for a simple, field-scale tool that can integrate soil properties, hydrology, and agricultural management practices (Sims 1998; Sharpley and Tunney 2000).

Lemunyon and Gilbert (1993) developed a field-scale tool, called the PI, to evaluate the vulnerability of sites to P losses in runoff. The PI is a qualitative, simple, educational, and practical screening tool for advisory agencies or crop consultants and farmers to use to identify the potential risk of P losses and choose the best management options to prevent P losses to water bodies (Gburek et al. 2000).

The original PI had eight characteristics: STP, inorganic fertilizer, organic fertilizer, fertilizer application amounts, fertilizer application methods, soil erosion, irrigation erosion, and soil runoff class (Lemunyon and Gilbert 1993; Sims et al. 2000). A rating value was assigned to each characteristic: low (1), medium (2), high (4), or very high (8), depending on risk level. A weighting factor was also assigned to each factor based on relative importance of each factor in contrib-

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Table 1
Soil properties to calculate the transport parameters of the P index.

Location	Soil series	*K* factors*	Slope (%)	Permeability (cm h^{-1})
Franklin County-1	Eram silty clay loam (fine, mixed, active, thermic Aquic Argiudolls) Lebo silty clay loam (loamy-skeletal, mixed, thermic Typic Hapludolls)	0.35	2.5	1.5 to 5.1
Franklin County-2	Woodson silt loam (fine, smectitic, mesic Pachic Argiaquolls)	0.35	1 to 1.5	0.5 to 1.5
Neosho County	Parsons silt loam (fine, mixed, active, thermic Mollic Albaqualfs)	0.40	1 to 3	1.5 to 5.1
Riley County	Smolan silt loam, Smolan silty clay loam (fine, smectitic, mesic Pachic Argiustolls)	0.185	5 to 6	0.5 to 1.5

* For the Revised Universal Soil Loss Equation.

uting to P losses in runoff. Each rating value was multiplied by the appropriate weighting factor. The PI value for each site is obtained by summing the products for all of the site characteristics. The PI values are then categorized into a specific site P loss vulnerability, ranging from low to very high.

The PI of Lemunyon and Gilbert (1993) and modifications thereof have been evaluated against actual runoff P losses. Sharpley (1995) found total P loss in runoff was closely related to the PI rating (r = 0.84) and concluded that the PI could be used as a reliable tool to estimate site vulnerability to P loss in runoff. Stevens et al. (1993) used the PI to evaluate site vulnerability to P loss in western Oregon and eastern Washington and found different PI values for various sites having different rates of erosion, STP content, and manure and fertilizer applications. They stated that further validation studies are needed to evaluate the PI. Eghball and Gilley (2001) used three rainfall-simulation studies to evaluate and modify the PI of Lemunyon and Gilbert (1993). They reported that correlation value (r) between total phosphorus (TP) and modified PI was 0.74, whereas bioavailable phosphorus (BioP) and soluble phosphorus (SolP) in runoff did not have a significant correlation with the PI rating. Sharpley et al. (2001) found that the PI developed for Pennsylvania had a strong relationship with dissolved phosphorus (DP) concentration (r = 0.94), P losses in runoff (r = 0.91), TP concentrations (r = 0.90), and TP losses in runoff (r = 0.89). The concept of storm return period has been incorporated into the Pennsylvania PI and can be used to more accurately determine P management restricted areas and their relative contributions to P losses (Sharpley et al. 2008).

Gburek et al. (2000) and Heathwaite et al. (2000) suggested some modifications to the original PI, such as a multiplicative determination of the PI, rather than an additive approach, and consideration of possible P contributions directly to streams by surface runoff. However, Eghball and Gilley (2001) conducted a study to evaluate the relative importance of the variables in the PI by using additive and multiplication methods and reported that additive PI values were more closely related with TP losses than were multiplicative PI values. The additive method of index calculation resulted in r values of 0.74 for TP and 0.77 for particulate phosphorus (PP), but the PI value calculated by the multiplicative method resulted in r values of 0.58 for TP and 0.55 for PP. The PI values calculated with either method were not significantly correlated with DP or BioP losses.

Whether using a multiplicative or additive method, a PI generates a value that must be interpreted with respect to P loss potential. Ideally, a PI would be calibrated against runoff studies, but there is no widespread agreement about the interpretation of runoff composition or runoff losses with respect to potential negative effects on surface waters. The P concentrations in runoff that are environmentally acceptable or unacceptable differs depending on the sensitivity of a water body to P, the intended uses of the water, and many socioeconomic factors associated with land use (Sims 1998; Sharpley et al. 2000, Sims et al. 2000). There are several general approaches to interpreting the results from runoff studies, including relative differences in P losses as influenced by management practice and site conditions, watershed-specific criteria that may be related to a total maximum daily load value, or comparison with the 1 mg P L^{-1} DP standard reported in some literature (Sims 1998). Elrashidi et al. (2003) also reported that a runoff P threshold of 5.0 kg ha^{-1} y^{-1} (4.47 lb ac^{-1} yr^{-1}) should raise awareness to a possible risk for surface waters. This value seems to be solely based on professional judgment.

All states were encouraged by the USDA Natural Resources Conservation Service to prepare a state-specific PI (Sharpley et al. 2002). The objectives of this study were to calibrate and modify the Kansas PI by using data collected from four runoff studies at different sites in Kansas.

Material and Methods

Data from four runoff studies in eastern Kansas were used in this study. Three of the studies used natural rainfall (Franklin County-1, Franklin County-2, Neosho County), and one was a rainfall-simulation study (Riley County). The crops included grain sorghum (*Sorghum bicolor* L. Moench) and soybeans (*Glycine max* L. Merr), for the studies using natural rainfall and wheat (*Tritucum aestivum* L.) and oats (*Avena sativa* L.) in the rainfall-simulator study. Treatments in the studies using natural rainfall were combinations of different tillage practices (conventional-till,

Table 2

The Kansas site assessment index-phosphorus tables below can be used to find the total source value and the total transport value. To begin, each site characteristic is assigned a P loss rating. The source characteristic ratings are summed to find the total source value (a). The transport characteristic ratings are summed to find the total transport value (b), and these two values are multiplied to find the P index value.

(a) Source characteristics

	Phosphorus loss ratings					Field value
Soil test P Bray P1 or Mehlic III STP Olsen STP (mg P kg^{-1})	<25 <10	25 to 40 10 to 20	40 to 60 20 to 30	60 to 75 30 to 40	>75 >40	
	1	2	4	8	10	
Fertilizer application rate (kg P ha^{-1})	0.10 × (kg P ha^{-1})					
Fertilizer application method	None applied	Was placed with a planter OR was injected deeper than 5 cm	Was incorporated after less than 3 weeks OR was surface applied more than 1 week	Was incorporated after less than 3 weeks and 3 months before planting OR was surface applied between 1 week and 3 weeks before planting	Was incorporated 3 months or more before crop planting OR was surface applied 3 weeks or more before crop planting OR was surface applied to pasture/hayfield	
	0	1	2	4	8	
Organic P application rate (kg P ha^{-1})	0.10 × (kg P ha^{-1})					
Organic P source application method	None applied	Was injected deeper than 5 cm	Was incorporated less than 3 weeks before planting OR was surface applied more than 1 week before planting	Was incorporated between 3 weeks and 3 months of planting OR was surface more than 1 week before planting	Was incorporated more than 3 months or was surface applied more than 3 weeks before crop crop planting OR was surface applied to pasture/hayfield	
	0	1	2	4	8	
					Total source value	

Table 2b continued

ridge-till, no-till), rates of inorganic P fertilizer (16, 24, and 45 kg P ha^{-1} [14.2, 21.4, and 40.2 lb ac^{-1}]), and fertilizer application methods (surface broadcast, surface broadcast incorporated, knifed). Phosphorus was applied as a liquid product containing 70 g N kg^{-1}, 95 g P kg^{-1}, and 58 g K kg^{-1} (Zeimen et al. 2006; Kimmell et al. 2001). Treatments in the rainfall-simulator study were combinations of incorporated cattle manure (0, 50, 100,150, and 200 Mg ha^{-1} [0, 44,650, 89,300, 133,950 and 178,600 lb ac^{-1}]) and cropped versus fallow. The manure had an average TP content of 3,500 mg kg^{-1} and a total N content of 7,400 mg kg^{-1} (Ethridge 2002). Basic soil characteristics are given in table 1. Soil samples were taken from 0 to 15 cm (0 to 6 in) in the rainfall studies each spring and at 0 to 5 cm (0 to 1.97 in) in the simulator study immediately before each simulated rainfall event. None of the sites were irrigated.

The size of the plots ranged from 0.25 ha to 1.47 ha (0.62 ac to 3.63 ac) for the Franklin County-1 site and were uniform at 0.41 ha (1.01 ac) for Neosho County site. For these two sites, runoff water was diverted through a weir at the downhill side of each

Table 2 continued

(b) Transport characteristics

	Phosphorus loss potential					Field value
Erosion (t ha^{-1})	2 × (t soil loss ha^{-1} y^{-1})					
Soil runoff class	Very low	Low	Medium	High	Very high	
	0	2	4	8	16	
Distance from field edge with lowest elevation to surface water	>152 m	91 to 152 m	61 to 91 m	30 to 61 m	0 to 30 m	
	0	2	4	8	16	
Furrow irrigation erosion	na	Tail water recovery QS < 6 very erodible soils QS < 10 Other soils	QS > 10 for erosion resistant soils	QS > 10 for erodible soils	QS > 6 for erodible soils	
	0	2	4	8	16	
Sprinkler system erosion/ runoff	na or little or no runoff indicated	LP on 0.3% slope, HP on 0-8% slope on non-sandy sites, and LP or HP on all sandy sites	HP on non-sandy sites> 8% slope, and LP on non-sandy sites 3% to 5% slopes	LP on non-sandy sites 5% to 8% slopes	LP on non-sandy sites 8% or steeper slopes	
	0	2	4	8	16	
					Total transport value	

Notes: STP = soil test phosphorus. na = not applicable. QS = the product of the water delivery rate to the furrow (Q), in gallons per minute, times the slope (S) in percent. LP = low pressure. HP = high pressure.

plot. ISCO samplers measured runoff volume and collected flow-weighted samples during runoff events (Zeimen et al. 2006). Plots were either 0.47×10^{-3} or 5.8×10^{-3} ha (1.16×10^{-3} or 14.3×10^{-3} ac) at the Franklin County-2 site. Runoff water from the plots was directed to sump pumps by 10 cm (3.9 in) diameter polyvinyl chloride (PVC) pipe. Runoff was then pumped through flow splitters set in the field. The splitters collected a portion of runoff water and stored it in polyurethane containers until the rainfall event ended (Kimmell et al. 2001). Runoff was collected from these three sites from April to November. The greatest amount of rainfall and the most intense storms occur in spring and summer in eastern Kansas, with little precipitation during the late fall and winter months. Therefore, an assumption was made that no runoff losses occurred from December through March, and the runoff collected from these sites was assumed to represent annual runoff.

For the Riley County site, runoff was collected from 0.15×10^{-3} ha (0.37×10^{-3} ac) plots during simulated precipitation in October of 1999 and May, July, and October of 2000. The rainfall simulator was built according to the specifications in Humphry et al. (2002). Each simulation had an intensity of ~10 cm h^{-1} (3.9 in hr^{-1}) and continued until runoff was collected for 30 minutes. All plots were pre-wet approximately 24 hours before each simulation to make antecedent moisture uniform. The sediment and P concentrations in runoff were essentially unchanged over the course of this study (Ethridge 2002). Annual losses of sediment and P were then estimated by multiplying the average runoff coefficient for the four simulations by the annual precipitation for the site and the average runoff composition.

Runoff samples were analyzed for bioavailable phosphorus (BioP), soluble phosphorus (SolP), and TP by standard methods. Total P concentrations were determined by the nitric-percloric acid digestion method (Kuo 1996). Bioavailable P was determined by a modification of the iron-oxide, filter-paper extraction method (Sharpley 1993). Soluble P was determined by filtering runoff water through a 0.45 μm (1.77×10^{-5} in) pore-size filter and measuring the concentration of the P in the filtrate. Phosphorus concentrations were determined according to the Murphy and Riley (1962) procedure.

Original Kansas Phosphorus Index and Calculation of Index Value. The Kansas PI as originally proposed is outlined in tables 2a and 2b and includes source factors (STP, rate and application method for P from fertilizers and manure) and transport factors (soil erosion, runoff class, distance from surface water bodies, and irrigation erosion). Each site characteristic influencing P loss is assigned a P loss rating. The sum of the P loss ratings for each source characteristic is multiplied by the sum of the P loss ratings for each transport characteristic. This product is the PI

Table 3
Site interpretation for phosphorus loss rating.

Phosphorus Index value		Site interpretation for Phosphorus Index value
0 to 75 75 to 100	Very low low	If current farming practices are continued, and site characteristics do not change, there is low probability of an adverse impact to surface waters from P losses at this site. Nitrogen-based nutrient management planning is satisfactory for this site.
150 to 300	Medium	Implement practice to reduce P losses by surface runoff and erosion. Consider crops with high P removal capacities. In most cases, P fertilizer will not be needed. Restrict manure application and a long-term P management plan should be used.
300 to 600	High	If current practices are continued, and site characteristics do not change, there is a risk of adverse impacts on surface water. Phosphorus management needs to be modified to reduce the risk of P movement. Use P-based nutrient management planning.
>600	Very high	Current practices are creating adverse impacts on surface water quality. Management practices should be modified to reduce hazards. Additional P applications are not warranted.

value and is used to provide the site interpretation (table 3).

Soil test P was categorized with a P loss rating of very low (0), low (2), medium (4), high (8), or very high (10). Bray P1 or Olsen's extractable P concentrations greater than 75 or 40 mg kg^{-1}, respectively, were designated as very high. Kansas State University Fertilizer Recommendations do not recommend any P fertilizer additions for any crop when Bray P1 or Olsen's extractable P concentrations exceed these values (Leikam et al. 2003). In this study, STP was determined by using Bray P1 concentrations of surface soil samples collected at each site. Inorganic and organic P application rates used in the runoff studies were multiplied by 0.1 to obtain the P loss rating. Phosphorus application methods, either organic or inorganic, were categorized into five subgroups: very low (0), low (1), medium (2), high (4), and very high (8). The P loss ratings range from 0 (no P applied) to 8 for surface applications that are not incorporated (table 2a) and likely represent a greater risk of P loss.

The P loss ratings for soil erosion factors were calculated by using the Revised Universal Soil Loss Equation and soil-survey information. Surface-runoff classes for each site were determined by the relationship between soil slope and soil-permeability class (table 4). Phosphorus loss ratings for soil-runoff class range from 0 to 16. The runoff studies did not allow the evaluation of distance from surface water bodies or irrigation erosion as site characteristics. Distance from the field edge to surface water was assigned as 61 to 91 m (200 to 300 ft) for all sites.

Sensitivity Analysis. A sensitivity analysis was done for the source and transport characteristics by doubling or halving the P loss rating values individually. The new PI values were then regressed against the actual bioavailable phosphorus (BioP), soluble phosphorus (SolP), and total phosphorus (TP) losses to determine the influence of the change of the P loss rating on the regression value. Regression models were chosen on the basis of statistical significance, correlation coefficient values, and standard errors. Those characteristics having a great influence on P loss rating were individually increased or decreased by a factor of five or ten to determine the effect, and these characteristics were combined together to obtain the best combination for predicting P loss.

Results and Discussion

Original Phosphorus Index. Phosphorus losses were strongly related to the PI values. The correlation coefficient values (r) were 0.94, 0.93, and 0.79 for BioP, SolP, and TP, respectively (figure 1a). Total P losses reached a plateau as the PI continued to increase, whereas the relationship between BioP and SolP losses and the PI rating was linear. Similarly, the results of Sharpley et al. (2001) from Pennsylvania PI found a strong relationship between their PI and P losses. The

Table 4
Soil permeability classes.

		Percentage slope				
Soil permeability*	Concave	0% to 1%	1% to 3%	3% to 6%	6% to 10%	>10%
Very rapid (>50 cm h^{-1})	VL	VL	VL	VL	VL	VL
Moderately rapid (5 to 15 cm h^{-1})	VL	VL	VL	L	L	M
Moderately slow (0.5 to 1.5 cm h^{-1})	VL	VL	L	M	M	H
Slow (0.15 to 0.5 cm h^{-1})	VL	L	M	H	H	VH
Very slow (<0.15 cm h^{-1})	VL	M	H	VH	VH	VH

Notes: VL = very low. L = low. M = medium. H = high. VH = very high.
* USDA NRCS 2009.

r values were 0.89 for TP and 0.91 for dissolved phosphorus (DP) losses. Eghball and Gilley (2001) also reported a strong relationship between PI and TP loss (r = 0.74) using a modified version of the PI from Lemunyon and Gilbert (1993), but they did not find a significant correlation with DP or BioP losses. The ability of the Texas PI to estimate P loss potential was evaluated by Harmel et al. (2005). They reported that Texas and Iowa P indices provided reasonable estimates of P loss with significant relationships ($p < 0.01$) between P index values and measured annual P loads. The P index values, Mehlich 3 STP, and poultry litter application rate had better correlation with DP concentrations and loads (r values ranged from 0.35 to 0.95) compared to TP and particulate phosphorus (PP) loads (r values ranged from 0.00 to 0.56). They stated that a weakness in the PI load estimations was using estimated annual average erosion instead of measured erosion. The r values increased from 0.49 to 0.76 when measured erosion was used instead of estimated erosion.

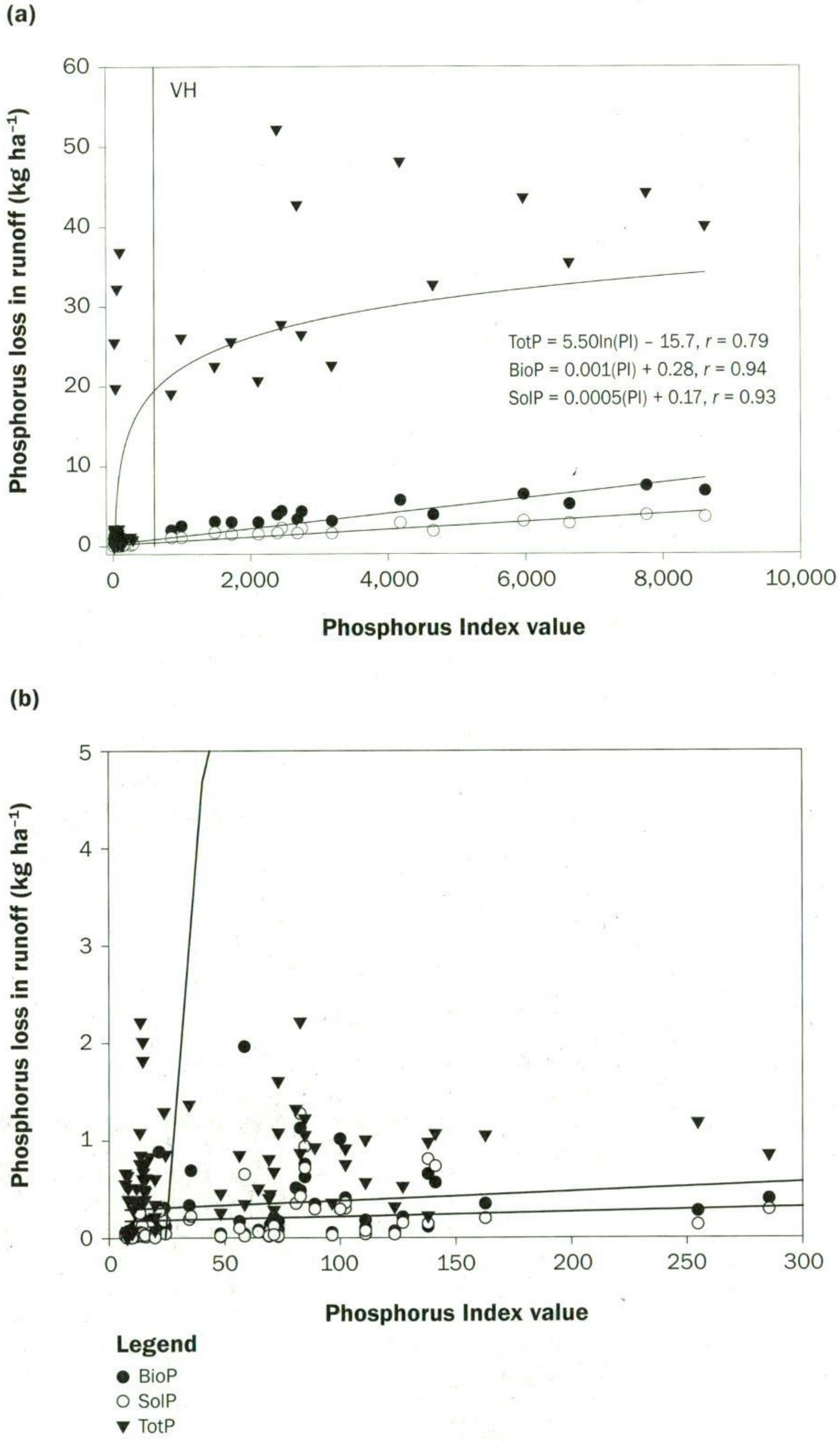
The correlation between PI rating and P losses was heavily influenced by the Riley County site, which used large manure applications (0 to 200 Mg ha^{-1} [178,600 lb ac^{-1}]) to evaluate a worst-case scenario. For small PI values, there was a cluster of data points near the origin of the figure 1a, with TP losses falling generally below the fitted curve (figure 1b). For small PI values, the PI is over-predicting actual losses.

The PI values ranged from 12 to 286 for the Franklin-1 site, 7 to 102 for the Franklin-2 site, 83 to 141 for the Neosho site, and 22 to 8,614 in Riley site. Of 90 plots at four different sites, 60% were ranked as having a very low vulnerability to P loss, 19% were ranked as low, 3% were ranked as medium, and 18% were ranked as very high (table 3). Except for the Riley County site, the majority of the plots were determined to have very low or low vulnerability to P loss. Thus, there is low probability of an adverse impact to surface waters from P losses at these sites. Most plots at the Riley County site ranked very high because of the manure applications, and P management needs to be modified to reduce P losses. Moreover, additional P applications are not warranted.

The Riley County site had extremely high PI values due to high manure rates used to evaluate a worst-case scenario. Large amounts of animal waste, generated in many

Figure 1

(a) Bioavailable, soluble, and total phosphorus losses versus the Phosphorus Index (PI) rating from the unmodified Kansas PI. (b) Bioavailable, soluble, and total phosphorus losses versus PI rating when the PI rating was <300. Curves are the same as shown in a.



Notes: VH = very high PI rating. BioP = Bioavailable phosphorus. SolP = soluble phosphorus. TotP = total phosphorus.

Table 5
The predictive value of the source and transport factors of the Kansas Phosphorus Index for bioavailable, soluble, and total-P losses in runoff.

Characteristics	Bioavailable P r*	Soluble P r*	Total P r*
Source factors			
Soil test P	0.84	0.66	0.84
Fertilizer application rate	0.14	0.01	0.33
Fertilizer application method	0.10	0.01	0.26
Organic P application rate	0.85	0.69	0.75
Organic P application method	0.84	0.66	0.84
Transport factors			
Erosion	0.75	0.57	0.87
Soil runoff class	0.46	0.45	0.45

* Based on linear correlation.

areas of United States, have been applied to agriculture fields as a means of improving soil properties and providing plant nutrients (Torbert et al. 2005). Beegle et al. (2000) reported that the increased number of animal feeding operations in localized areas has led to an accumulation of nutrients from manure that exceeds crop needs. Long-term and frequent applications of manure and biosolids results in very high STP concentrations because of imbalances between P inputs and outputs (Sharpley and Smith 1995; Sharpley et al. 1994; Beegle et al. 2000). Evaluation of PI for the areas having high STP and manure application can result in high PI values.

A runoff P threshold of 5 kg ha^{-1} y^{-1} (4.47 lb ac^{-1} yr^{-1}) was suggested by Elrashidi et al. (2003) as a trigger to raise awareness to possible risk for surface waters. All of the plots in these studies had a P loss less than 5 kg ha^{-1} y^{-1}, except those at the Riley County site. Similarly, 81% of all plots had dissolved phosphorus (DP) concentrations lower than 1 mg P L^{-1}.

Sensitivity Analysis and Modification of the Phosphorus Index. When individual source and transport factors were correlated with P losses in runoff, some characteristics were much more effective than others in predicting P losses (table 5). Soil test P, organic P rate and method, and soil erosion all have r values greater than 0.5. Soil runoff class produced values of 0.45 or higher. This information was used in the systematic sensitivity analysis.

Individually doubling or halving the PI value of source and transport characteristics did not make a remarkable change in the correlation coefficient values between PI values and P losses, although some characteristics had more effect than others (table 6). Those characteristics having a greater effect on P loss (table 5), compared with others, were multiplied or divided by a factor of five or ten to determine their effects on P loss, and those characteristics were also combined to find the best overall combination. Among all of the combinations considered, increasing the PI values by a factor of ten for STP and decreasing the PI values by half for erosion resulted in the highest r values, compared with other modifications. The r values were 0.97, 0.95, and 0.89 for bioavailable phosphorus (BioP), soluble phosphorus (SolP), and TP, respectively. These improvements were slight compared with the original PI. It seems that the Kansas PI is much less able to describe TP losses compared to BioP and SolP. Harmel et al. (2005) reported that a general limitation of the PI is its weakness to capture variability in annual soil erosion, causing error in annual P load estimates. The PI should describe not only total amount but also the primary form of P transported in runoff (Sharpley 1995). Stevens et al. (1993) reported that the PI predicts only the rate of soil movement off a particular field slope and does not give estimates of sediment transport and delivery for a water body. It was found that up to 90% of annual soil, runoff, and P loss can occur in only one or two intensive storms (Edwards and Owens 1991). However, PI uses annual runoff and erosional losses and average STP values. In general, the reliability of PI values will depend on the accuracy of the inputs such as runoff or sediment yield (Sharpley 1995). Therefore, correlations between runoff TP and PI or STP might not be as strong as the one between DP and PI or STP.

The P loss rating values for the modified PI ranged from 90 to 373 for the Franklin-1 site, from 62 to189 for the Franklin-2 site, from 142 to 267 for the Neosho site, and from 114 to 4,894 for the Riley site. Historically accepted average erosion losses in Kansas are approximately 15 Mg ha^{-1}(13,395 lb ac^{-1}). A typical organic P addition in Kansas is 80 kg P ha^{-1} (71.4 lb ac^{-1}), from a manure application rate calculated based on crop N removal rates, whereas the P addition would be 40 kg P ha^{-1} (35.7 lb ac^{-1}) if the application rate were calculated from crop P removal (Leikam et al. 2003). For N-based application, STP would typically be low, whereas P-based applications are used when STP is high. For these two scenarios, each characteristic in the PI was set at medium to generate a P loss rating which is denoted in figure 2. The modified PI predicts greater risk of P loss from P-based application because of the heavy weighting on STP. Of 90 plots at four different sites, 82% were under the division line for the organic P application based on crop N removal (figure 2). These sites could be ranked as having very low and low vulnerability to P loss. The remaining 18% were over the division line for the organic P application based on crop N removal. These sites could be ranked as having high and very high vulnerability to P loss.

Coale et al. (2002) evaluated Maryland P site index on 646 state-representative field sites beginning in the spring of 1999 through the spring of 2000. Out of these fields, 4% were determined as very high P, 8% were high, 19% were medium, and 69% were rated as low P loss potential. Soil test P levels (Mehlich-1 P) indicated that 55% of the evaluated field had an STP level less than 75 mg kg^{-1}. Coale et al. suggested that the Maryland P site index could serve as an adequate tool for identification of field P loss risk potential. Johnson et al. (2005)

Table 6

Influence of weighting factors on the relationship between the Kansas PI value and bioavailable, soluble, and total-P losses in runoff.

Characteristics	P loss rating	Bioavailable P r*	Soluble P r*	Total P r*
Soil test P	No change	0.94	0.93	0.79
	Half	0.94	0.93	0.79
	Double	0.95	0.94	0.81
Fertilizer application rate	No change	0.94	0.93	0.79
	Half	0.94	0.93	0.79
	Double	0.94	0.94	0.79
Organic P application rate	No change	0.94	0.93	0.79
	Half	0.94	0.93	0.79
	Double	0.94	0.95	0.79
Soil erosion	No change	0.94	0.93	0.79
	Half	0.95	0.95	0.80
	Double	0.93	0.93	0.79
Soil runoff class	No change	0.94	0.93	0.79
	Half	0.94	0.93	0.79
	Double	0.95	0.94	0.80
Soil test P	10-fold	0.96	0.95	0.87
10 × STP + ½ erosion†		0.97	0.95	0.89

Note: STP = Soil test P.

* Based on linear correlation.

† Best equation for maximizing the r values associated with bioavailable P, soluble P, and total P.

applied the P Loss Assessment Tool on farms throughout North Carolina to predict the farms that will be forced to change management practices and reported that the P Loss Assessment Tool performed well to predict the areas in the state that are known to be disproportionately susceptible to P loss due to variable soil characteristics.

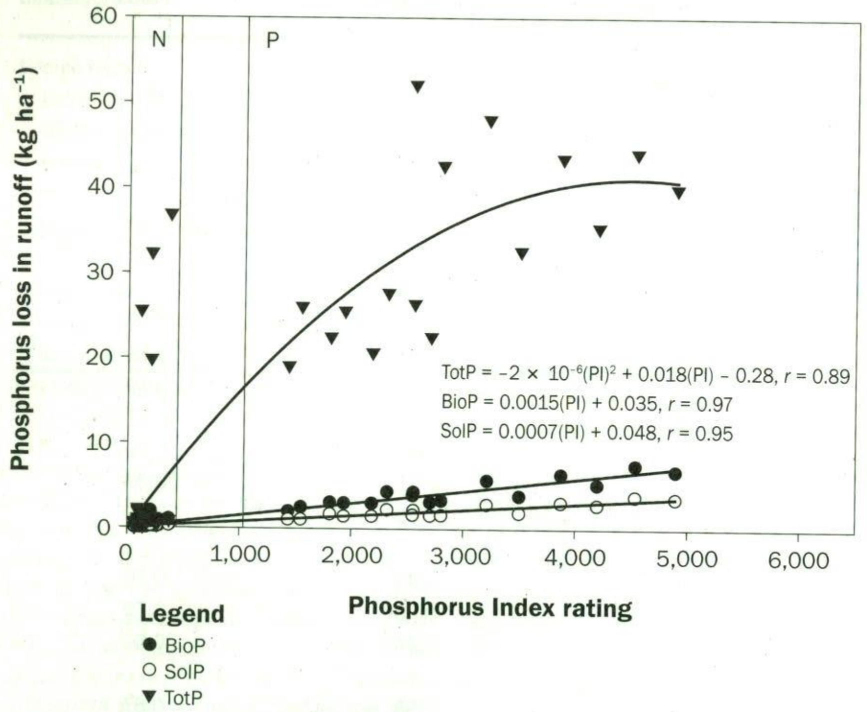
Effects of Soil Test Phosphorus on Phosphorus Losses and Concentrations in Runoff. Soil test P thresholds are an alternative to a PI for predicting relative risk of P loss. Soil test P has been shown to accurately predict P concentrations in runoff (Pote et al. 1996; Cox and Hendricks 2000; Torbert et al. 2002) and DP in leachate (McDowell and Sharpley 2001; Hansen et al. 2002), although it can not assess the transport potential and this relationship is soil-specific and dependent on soil and site characteristics (Pote et al.1999; Cox and Hendricks 2000; Davis et al. 2005). However, STP offers simplicity over a PI approach.

In this study, STP was also a good indicator of P concentration in runoff (figure 3). Pote et al. (1996) reported that there were strong relationships between STPs (Mehlich 3, Bray-P1, Olsen) and dissolved reactive phosphorus (DRP) or BioP concentration in runoff (r values < 0.87). Cox and Hendricks (2000) found a relationship between STP (Mehlich-3) and DP concentration in runoff. The authors stated that increasing Mehlich-3 P increased DP concentration in runoff. Similar results were reported by Torbert et al. (2002). Davis et al. (2005) also reported that the DRP and total phosphorus (TP) concentrations in runoff were highly correlated with Mehlich-3 P for individual soil series (r = 0.96 and 0.97 for DRP and r = 0.90 and 0.96 for TP). Vadas et al. (2005) studied the relationship between STP and runoff DP using a single extraction coefficient for water quality modeling. They used published data from 17 studies that measured extraction coefficient using Bray-P1, Mehlich-3, water extractable soil P, or soil P sorption saturation (%). They reported that there was a strong relationship between runoff filterable reactive P and agronomic STP (Bray-P1 and Mehlich-3), or environmentally oriented water extraction test with no difference among those tests. However, the Mehlich-3 soil P might be more effective compared to Bray-P1 test for calcareous soils. Moreover, they stated that soil P saturation may provide the most universal prediction of DP in runoff but only non-calcareous soils.

Hively et al. (2005) reported that total DP concentrations in runoff from the sites without fresh manure were strongly correlated with Morgan's STP (r = 0.92). Vadas et al. (2007) found that runoff DP concentrations were well related to manure water extractable P. They stated that after manure application, runoff DP concentrations were greatest for the first event and decreased steadily through time, although they remained higher compared to P concentrations from control plots. Long after manure applications ceased, contributions of DP to runoff continued. Daniel et al. (1993) found a poor relationship between STP and DRP in runoff and stated that STP alone was not a satisfactory estimator of DRP. Moreover, Kleinman et al.

Figure 2

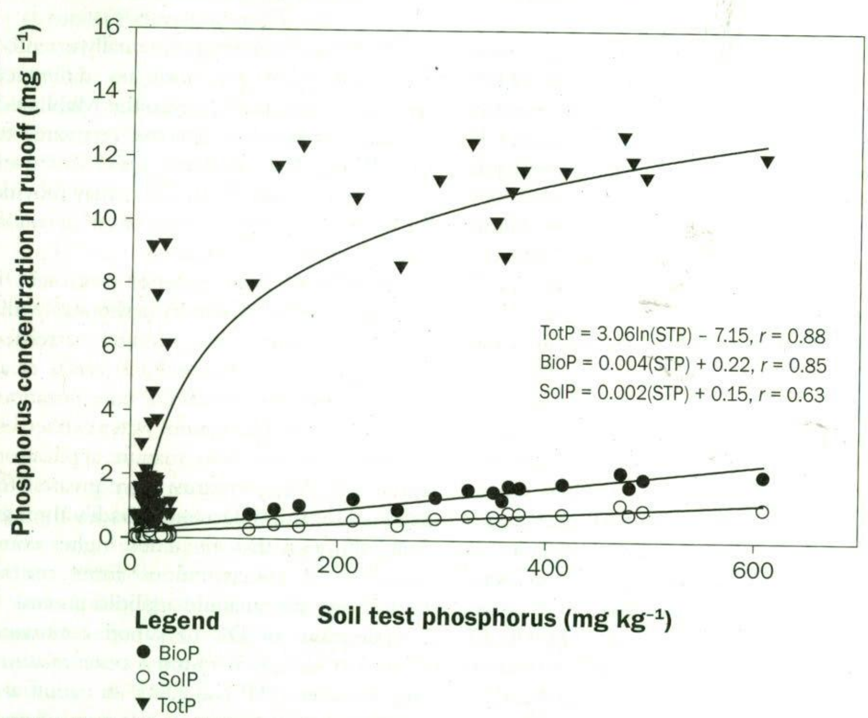
Bioavailable, soluble, and total phosphorus losses versus the modified PI rating.



Notes: PI = phosphorus index. N = N-based manure application. P = P-based manure application. BioP = Bioavailable phosphorus. SolP = soluble phosphorus. TotP = total phosphorus.

Figure 3

The relationship between soil test P (Bray P1) and P concentration in runoff.



Notes: BioP = Bioavailable phosphorus. SolP = soluble phosphorus. TotP = total phosphorus. STP = soil test phosphorus.

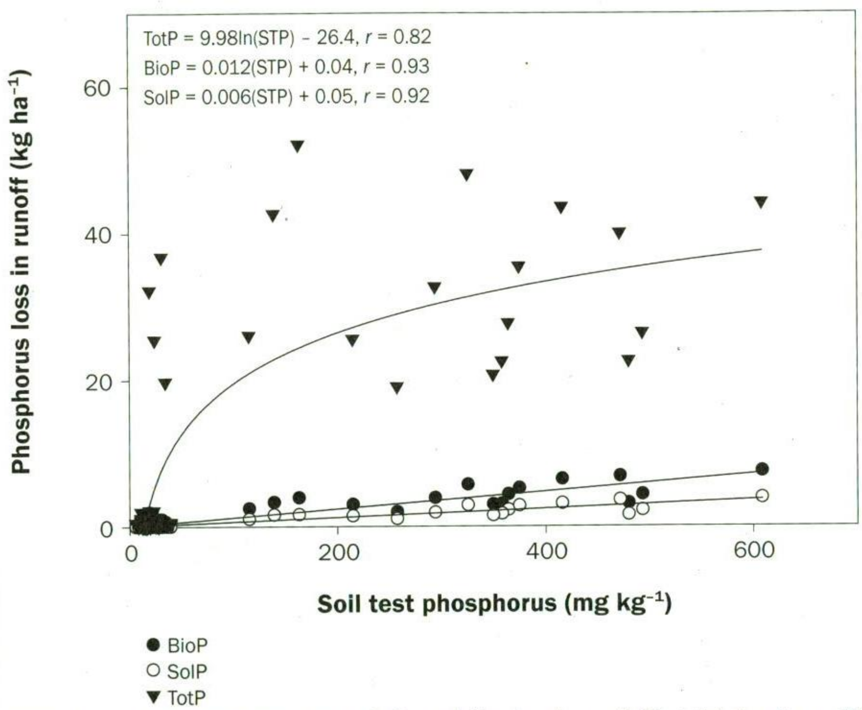
reported that STP plays an important role in determination of P in runoff. However, there are also other influencing factors such as soil type, slope, erosion, landscape position, and nutrient application (2002).

Recent application of manure can produce high total DP concentration and overwhelm the effect of STP (Kleinman et al. 2002). Burch et al. (2001) reported that on heavily manured soils, there was a nonlinear diminishing relationship between Mehlich-3 STP and DP concentrations in runoff. Sauer et al. (2000) also found a strong relationship between Mehlich-3 STP and DRP concentrations in runoff existed before litter application, but DP application rates overwhelmed the effects of STP when litter was applied. Similar results were reported by Delaune et al. (2004). Sauer et al. (2000) concluded that STP can be useful for estimation of runoff DRP only in areas where high DRP in manure or other sources are not applied. Some studies revealed that particulate phosphorus (PP) was the predominant form of P in runoff and related to STP, where as some found DRP to be predominant P form in runoff due to the differences among the studies such as slope, erosion, climate, and grazing animals (Hart et al. 2004). However, most studies mentioned earlier reported a strong relationship between STP and DRP, PP, or TP in runoff. Our results indicated that STP was well correlated with P concentrations in runoff, with r values of 0.85, 0.63, and 0.88 for BioP, SolP, and TP, respectively (figure 3). Total P concentration in runoff increased rapidly to a point corresponding to 100 mg kg^{-1} of STP at which point TP increased more slowly while BioP and SolP concentrations increased in a linear fashion (figure 3).

There can be a direct correlation between STP and the amount of P losses (Pote et al. 1996; Pote et al.1999; Davis et al. 2005). Pote et al.(1999) reported that DRP load in runoff was highly correlated with water extractable P for three different Ultisols. Davis et al. (2005) found that DRP load was highly related to Mehlich-3 P, for three different soils (r of 0.95, 0.95, and 0.95), and water-soluble P ($r > 0.88$). Sharpley and Moyer (2000) studied forms of P in manure and compost and their release during simulated rainfall and reported strong correlation values (r) between amount of P leached and the amount of water extractable inorganic P (0.98) or organic P (0.99) of each material. However, a weak correlation of STP with DRP and BioP load ($r < 0.42$) because of highly variable runoff volumes was also reported by Pote et al. (1996).

Our results showed that STP had a strong relationship with P losses, with r values of 0.93, 0.92, and 0.82 for BioP, SolP, and TP, respectively (figure 4). Total P losses increased rapidly as STP continued to increase up to a value of 150 mg kg^{-1}, at which point the increases in total P slowed whereas BioP and SolP increases were slow and linear. Using the PI to predict P losses or using STP as a single factor produced similar results. However, using an edge of field interpretation may mislead management planning in a situation in which there is no connectivity to any surface water bodies or in which transport potential is low. Moreover, STP methods were originally defined for agronomic aspects and not for environmental purposes (Sims 1998; Sharpley and Tunney 2000; Sims et al. 2000). For example, there are some differences in the sampling and handling of soil samples. Agronomic samples are generally taken from 0 to 15 cm (0 to 6 in), whereas a 5 cm (1.97 in) depth is more useful for environmental purposes (Sims 1998; Sims et al. 2000; Sharpley and Tunney 2000; Torbert et al. 2002).

Figure 4
The relationship between soil test P (Bray P1) on P loss in runoff.



Notes: BioP = Bioavailable phosphorus. SolP = soluble phosphorus. TotP = total phosphorus. STP = soil test phosphorus.

Summary and Conclusions

The Kansas PI performed well for all sites as a whole. The correlation between PI values and P losses was heavily influenced by the Riley County site because of very high manure applications. The Kansas PI did not take into account the residual effects of fertilizer. By modification of the Kansas PI, we improved the r values to 0.97 for BioP, 0.95 for SolP, and 0.89 for TP. Our sensitivity analyses showed that the source and transport characteristics were not sensitive to factors that influenced P loss in runoff. Of the 90 plots at four different sites, plots from Neosho, and Franklin-1 and 2 sites were ranked as having very low and low vulnerability to P loss (82%), whereas plots in the Riley County site were ranked as high and very high vulnerability to P loss (18%) due to manure applications. Therefore, P management strategies need to be modified to reduce P losses on this site. Moreover, additional P applications are not warranted for this site. Using STP as a single factor to predict P losses in runoff for our sites produced results similar to using the PI.

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